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Acoustical Imaging System Evaluation

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NOTICE

FOREWORD

The work described in this report, Acoustical Imaging System Evaluation, was performed by the Propellant Development Branch, Solid Rocket Division, of the Air Force Rocket Propulsion Laboratory (AFRPL), Edwards Air Force Base, California, 93523-5000, during the period 1 May 1984 to 31 May 1985.

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A non-destructive evaluation device was delivered to the AFRPL by Battelle Laboratories. The sensitivity and other operational limitations of the device were not known, and a project was initiated at the AFRPL to determine those parameters. Sensitivities for both the through transmission subsystem and the pulse echo subsystem were determined. Both techniques use ultrasound to detect inner bore cracks in the propellant grains, and case/liner debonds (respectively) in tactical missile motors. In addition, the limitations of the mechanical subsystem and the transducer head geometry were investigated. Several inert analog motor sections, with both metal and phenolic cases, were used in the investigation, including a full size inert Sidewinder motor. The goal for the technology is to produce a field-usable motor health monitor for the DoD.

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BACKGROUND

A problem common to all solid propellant rocket motors is that with age and handling, the propellant will eventually become defective. These defects, cracks or debonds in the propellant grain, can cause a burn rate increase, a corresponding burn characteristic change, and even a potentially catastrophic motor failure. In a tactical missile system such a failure could result in the loss of not only the missile, but also the loss of an aircraft and its pilot. To prevent such a catastrophe, the Air Force currently rotates its stock of tactical missile motors to an X-ray facility located at Hill AFB, Utah, where they are nondestructively tested/inspected to determine propellant quality. This technique, hazardous to inspecting personnel, is costly and results in a prolonged reduction in the weapon system's ready inventory at the depot level. Recently an alternate method of nondestructive testing (NDT), which uses ultrasonic energy to image defects in propellant grains, has been made available. This new method is inexpensive, accurate, safe, and can be used right at the depot.

Using this new ultrasonic technology, Battelle Pacific Northwest Laboratories constructed an Acoustical Imaging System (AIS) (Ref. 1) for the Air Force Rocket Propulsion Laboratory (AFRPL). In February 1984 Battelle delivered the system to the AFRPL and verified that the AIS did work as it was supposed to. This verification gave no indication of the system's actual sensitivity limits. To determine that sensitivity, an in-house program titled "NDT Evaluation" was started in May 1984.

A concurrent literature search was conducted to determine how big a crack or a debond could become before it started adversely affecting motor burn characteristics. Unfortunately, there was no information to be found. (Similar work with ultrasonics done at the AFRPL some years ago applied to ballistic missile motors.)

To measure the effectiveness of the AIS, we compared AIS test results with X-ray test results. Hill AFB X-ray experts said that their machines can see debonds 1/8-in. x 1/8-in. x 1/32-in. and 1/64-in. wide cracks (supposedly any length crack can be detected). As will be seen, this is very close to the detectability limits of the AIS.

The ultimate goal for this type of ultrasonic technology is to put missile X-ray inspection out of business. Using the AIS demonstrated technology, it will be possible to build motor health monitors to inspect the motors right in the depot more often and at lower cost than current X-ray inspection.

OBJECTIVE

The objective of this study was to determine the sensitivity and repeatability limitations of the Battelle AIS in a laboratory environment. The study was to be considered a success if the system could detect a debond 3/8 inch X 3/8 inch, and a crack 5/16 inch long.

APPROACH

Flaws were manufactured in the inert propellant grains of several test articles which closely simulated a tactical missile motor configuration. These test articles were then inspected using the AIS, and the machine adjusted to produce an optimum signal to detect each flaw. With the signal optimized, repeatability tests were run. If the signal was repeatable, the flaw was recorded as detectable. The process was repeated for the next smaller flaw until a repeatable signal was no longer obtained. In this manner the exact sensitivity of the system was determined. An experiment was also run to determine any problems associated with imaging the propellant's boost grain area. All of these tests were run for both the machine's Inner Bore Crack (IBC) subsystem and its Debond subsystem.

EXPERIMENT

The Acoustical Imaging System

The Battelle laboratory's prototype AIS uses ultrasonic energy at a frequency of 58 KHz to image defects in small rocket motor propellant grains. The AIS is an imaging system and does not employ acoustic holography (for further discussion of holography vs imaging, see Appendix A). The system detects two types of solid propellant motor flaws; debonds between the various layers of materials that make up the motor, and cracks on the inner bore of

the propellant grain. The AIS employs two different ultrasonic imaging techniques to detect these flaws. A pulse-echo technique is used to image debonds, and a through-transmission test is used to detect inner bore cracks. Basically, both tests send an ultrasonic signal through the motor case into the propellant. If no flaws (air gaps) block the signal, it reflects off the inner bore and returns unchanged. If there is a flaw, the signal will reflect off of it instead of the inner bore and the system's software will interpret this accordingly. Finally, the AIS provides a printed map of the rocket motor showing the location and extent of any detected flaws.

The pulse-echo subsystem is designed so that the operator may adjust its sensitivity four different ways. The operator may: first, position the transducer which serves much the same purpose as focusing a lens; second, select the received signal attenuation level; third, position an electronic gate which determines what part of the received signal is used by the computer for its calculation; and fourth, position the transducer over a normal (i.e., nondefective) motor section so that the computer can record a reference voltage level to use as a comparison in later calculations. Ensuing scan sensitivity is dependent on this voltage reading which unfortunately is not at all consistent over the motor's normal areas. Similarly, the through transmission subsystem allows the operator three ways to adjust scan sensitivity. The operator may: first, position the two transducer heads (It was particularly difficult to adjust these transducers to receive an acceptable signal.); second, adjust the threshold voltage level (If the received signal falls below the threshold level, a defect is recorded.); and third, adjust the peak voltage level of the received signal. For both subsystems a scan time of about 10 minutes is typical for an 8-inch long, 6-inch diameter motor section. Printer output lags behind the received signal by about one scan length. (For details on the AIS, see Ref. 1).

Test Articles

Five inert test articles were used to test the AIS:

1. TA1, an 18-inch section cut from an inert Sidewinder missile motor, has a large (2-in x 2-in) section of propellant cut from it which Battelle

used for system verification. We only used TA1 to familiarize ourselves with the machine.

2. TA2 was also an 18-inch Sidewinder section. Five debonds of varying sizes and types (case/liner, liner/propellant, and two kissing debonds) were hand cut in one end of the section (see Fig. 1a). Three naturally occurring cracks were found in the middle of the section (see Fig. 1b). At the opposite end, four inner bore defects of varying lengths, depths, and widths were cut (Fig. 1c). Due to inaccuracies in measuring the cuts, no definitive conclusions were drawn from the TA2 test runs, but the tests did give us a good idea of the Batelle machine's capabilities and guided us in manufacturing TA4.

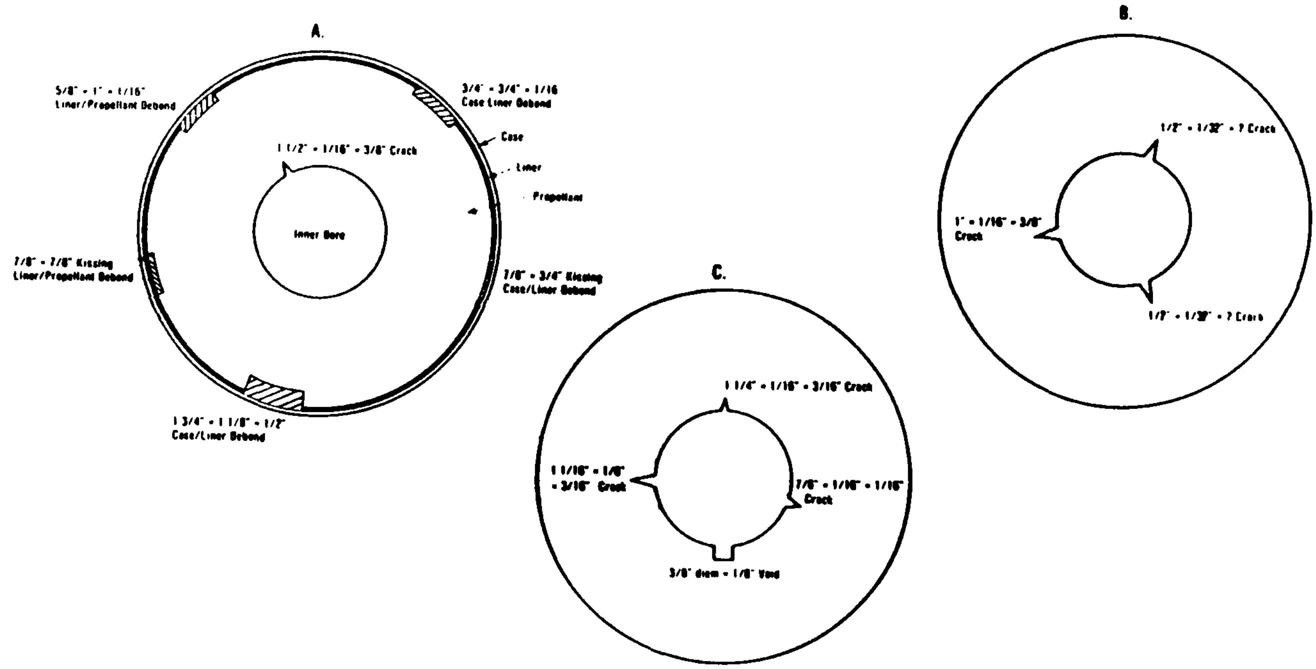

Figure 1. Test Article 2 (Inert Sidewinder Section). A) Debond End, B) Middle, C) Crack End. All dimensions are length x width x depth.

3. TA3, a phenolic container BATES grain with one debond and one crack hand cut into it, was tested to verify that the AIS could "see through" phenolic containers.

4. TA4, an inert BATES grain that the AFRPL Propellant Laboratory prepared especially for this program, used a phenolic container and an inert propellant that closely simulates the Sidewinder propellant. Teflon shims cut to specific sizes were glued to the mandrel to simulate inner bore cracks and glued to the inside of the case to simulate debonds. Once the vacuum poured propellant set, the shims could easily be removed leaving an air gap of precise dimensions. Two teflon rods were inserted in the middle of the grain to simulate voids in the propellant (see Fig. 2). TA4 was used in the experiment's final phase to determine AIS's exact sensitivity. Note that TA4 does not have a liner. Since the acoustic properties of the liner and the propellant are very similar, and since we knew the AIS could not detect a liner/propellant debond, we decided not to include a liner in the test article, saving us time and reducing the complexity of the manufacturing task.

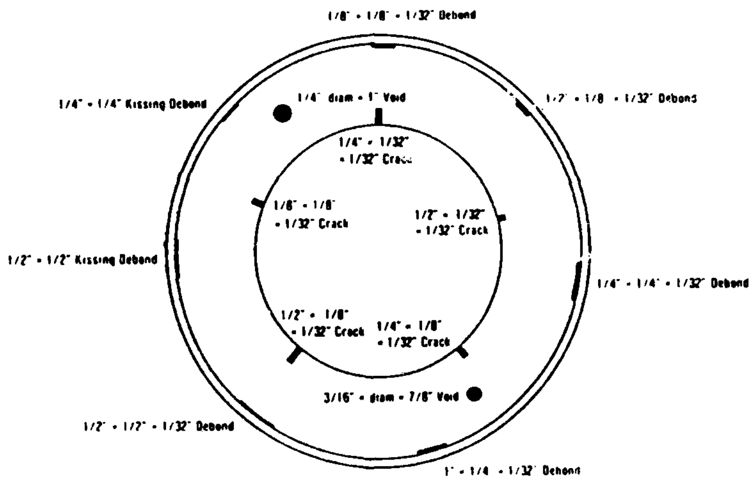

Figure 2. Test Article 4 (Composite Case BATES). All Dimensions are length x width x depth.

5. TA5 is a full length inert Sidewinder motor. Several attempts to cut precision flaws into its grain failed. Ultimately, TA5 was used to test the AIS's mechanical abilities on a lifelike case configuration, and to test its ability to detect a flaw in a boost grain (star).

Method

This experiment was conducted in three phases; a familiarization phase, a

narrowing phase, and a specification phase. In the first phase the project manager, project engineer and technicians familiarized themselves with the operation of the AIS using TA1. A thorough Battelle operations manual and a very user-friendly computer program greatly facilitated this process. During this phase of the program, work was also started on manufacturing flaws of known size into the bore of TA5. Several methods were attempted, including rotary blade cutting, shaped metal blade cutting, and heated blade cutting, but none produced the desired results, and TA5 was put aside. The second phase was devoted to narrowing the sensitivity of the AIS to a rough range of flaw sizes. To do this, both debond and inner bore flaws of various sizes were hand cut into TA2. The motor section was scanned many times until an optimum sensitivity was obtained. This was done for both the pulse echo subsystem and the through transmission subsystem. During this phase it was discovered that the AIS would not pick up a kissing (or closed) debond, a closed crack or a liner/propellant debond. The AIS had no trouble picking up (with good repeatability) a 3/4-in. x 3/4-in. x 1/16-in. case/liner debond, which was the smallest case/liner debond that had been cut (Fig. 3). The smallest inner bore defect was a 7/8-in. x 1/32-in. x 1/16-in. crack, and there were indications, though not very repeatable, that the AIS was picking it up (Fig. 4). From this information we were able to design an accurate and useful

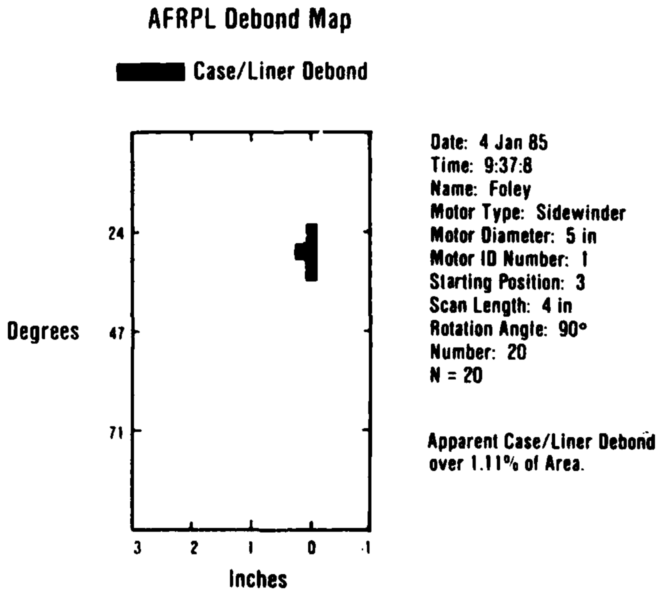

Figure 3. AIS Scan of a 3.4" long x 3/4" wide x 1/16" deep Case/Liner Debond in TA2.

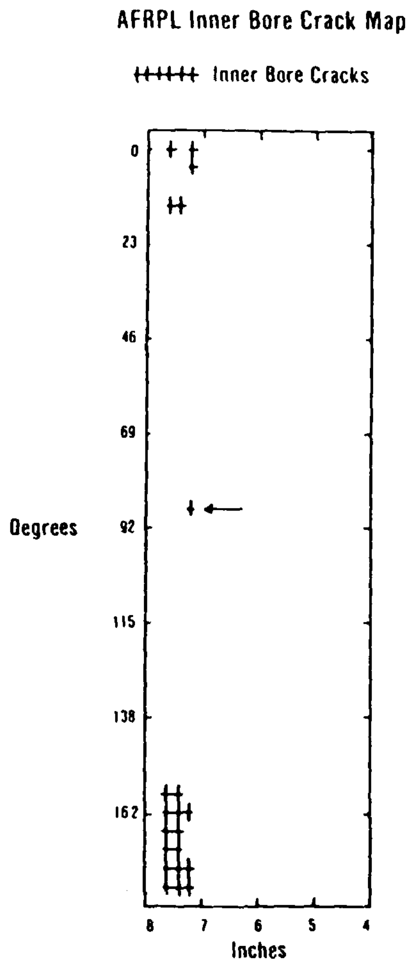

Figure 4. AIS Scan of a Crack (Arrow) 7/8" long x 1/32" wide x 1/16" deep.

analog in the form of TA4. The final phase of the program involved determining exactly what the sensitivity of the AIS was. Since the TA5 effort was at a standstill, an alternate precision test article had to be made. The design for TA4 was suggested, but since the only containers available for BATES motors are phenolic, the AIS had to be checked out on a composite motor section. To do this, defects similar to those in TA2 were cut into TA3. TA3 was then scanned and the results were compared to the TA2 scans. The comparison for both the pulse-echo and the through transmission scans was favorable. TA4 was then manufactured and tested. Also, as part of this phase the full size inert Sidewinder motor, TA5, was scanned.

Repeatability in these experiments is a measure of how interpretable the

data is. It is not just a measure of whether or not the same defect showed up repeatedly in consecutive scans, but takes into account the location and clarity of the defect indication, as well as the amount of background noise that came through on the scan. Repeatability estimates, given hereafter, are just that - estimates. They reflect the experimenters confidence in the reliability and interpretability of the flaw data.

RESULTS

The pulse-echo subsystem can detect a 1/8-in. x 1/8-in. x 1/32-in. case/liner debond with very high repeatability (Fig. 5). A software change, not currently available at the AFRPL, must be made for the system to detect liner/propellant debonds. However, Ref. 1 states that the results of Battelle's liner/propellant debond work were poor.

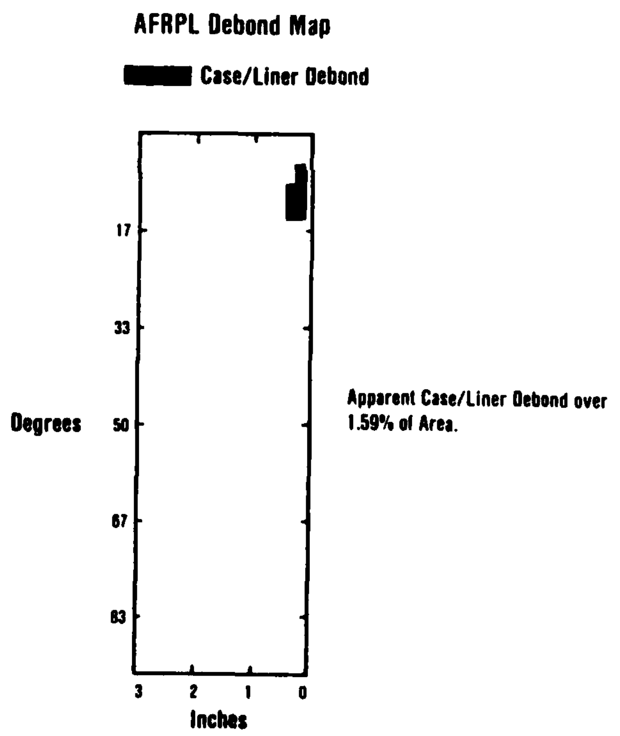

Figure 5. AIS Scan of a Debond 1/8" long x 1/8" wide x 1/32" deep in TA4.

The through transmission system consistently detected 1/8-in. x 1/32-in. x 1/8-in. cracks with only a medium repeatability. (Note the noise problem shown in Fig. 6.) The through transmission system could also detect a 1-in. x 1/4-in. void located in the propellant half way between the case and the inner bore of the BATES grain (about 3/4 inch from the bore). Repeatability for void detection is low because the indication on the map is vague compared to the size of the flaw (Fig. 7).

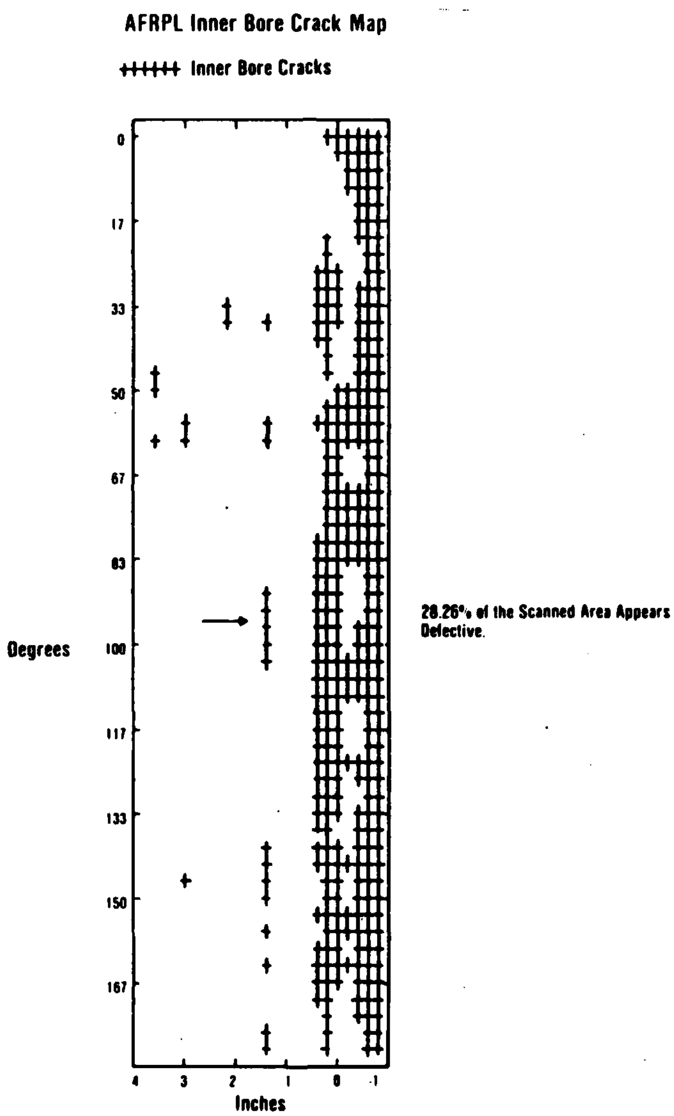

Figure 6. AIS Scan of a Crack (Arrow) 1/8" long x 1/32" wide x 1/8" deep in TA4.

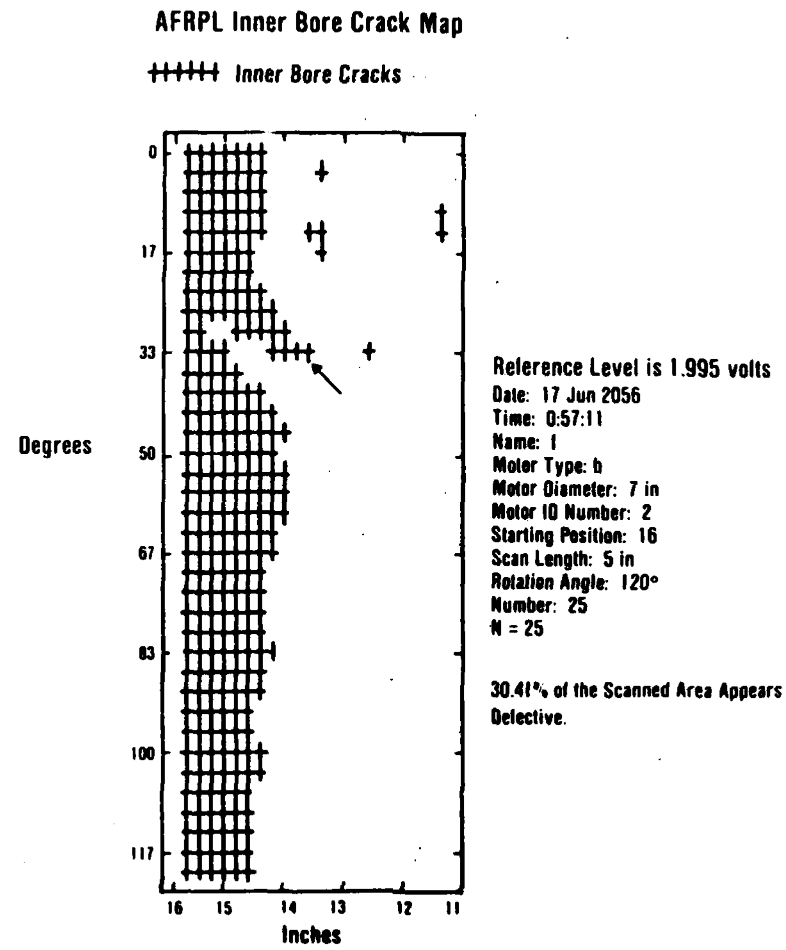

Figure 7. AIS Scan of a Void, 1" long x 1/4" diameter in TA4.

During tests run on TA5 and other articles, several AIS limitations were discovered. Because of the limitations of the mechanical subsystem, certain portions of the full length motor could not be examined. There are projections where the missile's fins are attached that interfere with transducer motion, and so it was impossible for us to gather any information from the motor's slotted grain area. Certain motor case decals can interfere with the ultrasonic energy transmission through the case and sometimes are indicated as defects on the scan plot. It is important to maintain good water coupling between the transducers and the case, as a bad coupling can also cause a flaw indication. Through-transmission transducers looking for inner bore cracks will show a debond as a double flaw indication, and will also show an improperly focused inner bore defect as a double flaw indication.

CONSIDERATIONS

The system, as it is, does not operate at an optimal frequency. The motor case's small diameter compared to transducer head size (specifically, the through transmission transducers) limits the frequency range which will work for flaw detection. The frequency currently used, 58 KHz, is much too low for this application and severely limits the machine's sensitivity. Similar ballistic missile motor experiments (Ref. 2) yielded much better results because the motor's geometry allowed use of a higher frequency. One possible solution to the problem is to design a set of transducer heads to improve ultrasonic energy focusing. Conversations with transducer manufacturing experts have led me to believe that the technology exists to build such a transducer; technology which was unavailable when Battelle built the AIS. I believe transducers can be designed to work around the motor case irregularities that now interfere with the scanning process. Before any design work is initiated, Air Force needs must be carefully defined. Battelle's AIS may already meet current critical flaw size detection requirements.

CONCLUSIONS AND RECOMMENDATIONS

It has been clearly demonstrated that the AFRPL Acoustic Imaging System can reliably detect inner bore flaws and case/liner debonds. Small 1/4 in. x 1/32 in. x 1/16 in. cracks were detected with low repeatability. However, more realistically sized naturally occurring 1-in. x 1/16-in. x 3/8-in. cracks could be detected with high repeatability (Fig. 8). The smallest nonkissing case/liner 1/8-in. x 1/8-in. x 1/32-in. debond tested could be very reliably detected.

The present system drawbacks are that it will not detect a kissing flaw or a liner/propellant debond. The project directive states that the project will be considered a success if the system can image a debond 3/8 inch x 3/8 inch, and a crack 5/16 inch long. By these standards the AIS has exceeded expectations. Taking into consideration all that has been learned in this program, acoustic imaging appears to be ideally suited for motor health

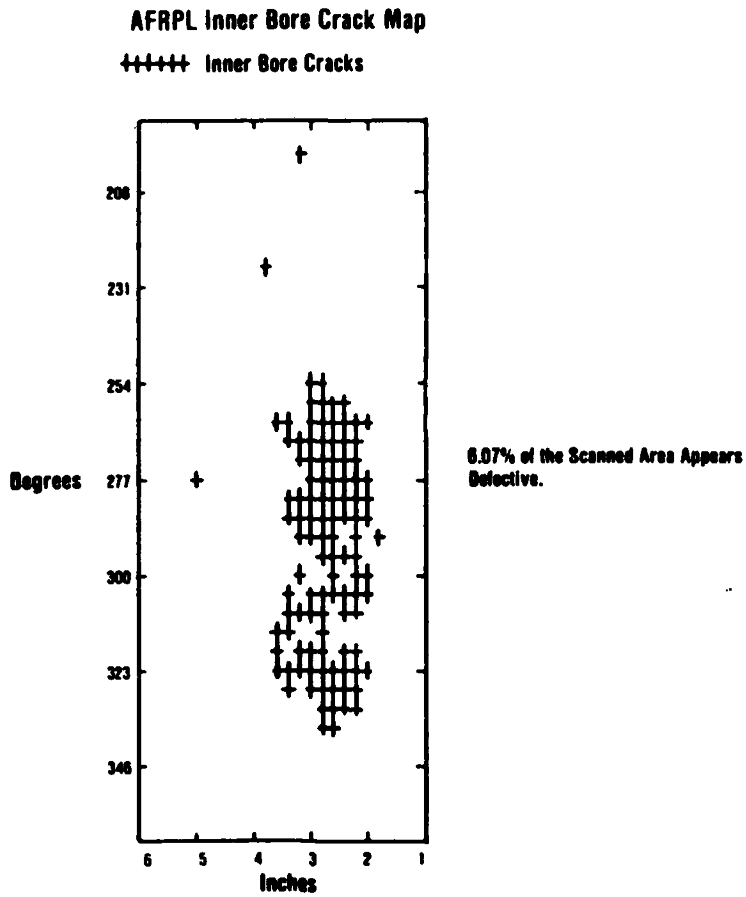

Figure 8. AIS Scan of a Crack 1" long x 1/16" wide x 3/8" deep in TA2.

monitor applications. There is sufficient evidence to show its promise and to indicate the direction development of a field-usable motor health monitor based on the AIS technique should take.

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1. Collins, Dale H., et al, An Acoustical Imaging System for the Inspection of Solid Rocket Motors, AFRPL-TR-84-002, Battelle Pacific Northwest Laboratories, Richland, Wash., January 1984.

2. Collins, Dale H., Diversification of Acoustical Holography as a Non-Destructive Inspection Technique to Determine Aging Damage in Solid Rocket Motors, AFRPL-TR-76-37, Battelle Pacific Northwest Laboratories, Richland, Wash., April 1976.

Appendix A

Acoustic Imaging vs Acoustical Holography

Acoustical Imaging and Acoustical Holography are very similar ultrasonic imaging techniques. The basic difference is that holography supplies information in three dimensions while imaging gives only two dimensional data. Both techniques can use either the pulse-echo or through transmission method of data collection. In the pulse-echo mode, the ultrasound device transmits an ultrasonic pulse from a single transducer, through the motor case (taking care not to resonate the case) and into the propellant. Because the propellant is a polymer and thus highly attenuative to sound waves, a high energy (high frequency) wave is preferable for maximum penetration and sensitivity. When the pulse hits the bore of the motor, which is made of air and thus has a much lower impedance than the propellant grain, it is partially transmitted and partially reflected back towards the case. Since there is such a big difference in impedances, most of the pulse is reflected. The reflected pulse is then received by the same transducer and the cycle is complete. If that pulse encounters an air gap such as between the case and the liner, it will reflect back just as it did from the bore. This reflection, however, will be much stronger than the bore reflection and the computer will be able to detect it as a flaw.

In an imaging technique the computer receives only shadow information. That is, the computer can tell only the cross-sectional area of the flaw, not its depth within the grain or its width. Holography, on the other hand, supplies enough information for the computer to be able to calculate the depth of the flaw. In holography the initial ultrasonic pulse is recorded, and phase information about it is stored. When the pulse returns, its phase changes can be compared with its original phase and information about that third dimension, depth, can be calculated. In this way, not only can you know depth below the surface, but also how deep the defect itself goes.

The through transmission mode of the ultrasound equipment can also employ holography, or an imaging technique. To image a defect, an ultrasonic pulse is transmitted from one of two transducers. The shape and position of the transducers focus the low frequency pulse on the motor's inner bore

where it is deflected to the receiving transducer. The angle at which the pulse travels through the propellant is such that any radial defect in the bore (such as a crack) will block the signal. Obtaining a hologram of the same defect simply involves recording phase information about the initial and returned pulses and comparing that information as before. A somewhat complex computer program can reconstruct that data into a three dimensional representation of the flaw.

It is difficult to compare the relative sensitivities of the two techniques. Holography, which showed great promise on ballistic missile motors, has never been used in smaller motor applications. Imaging techniques provide sufficient data for accurate damage analysis. Holography's added complexity makes it a less desirable NDT technique unless it provides a considerable increase in sensitivity.